Recent Electroweak Results from DØ

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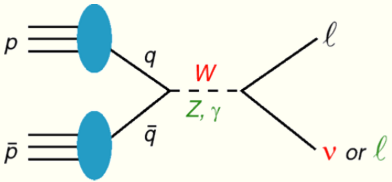
Outline

1. Introduction
   - Electroweak Physics
   - The DØ Experiment
2. Z Transverse Momentum Spectrum in 1 fb^{-1}
3. Photon ID
4. Dibosons
   - $Z\gamma$ in 1 fb^{-1}
   - $W\gamma$ Radiation Amplitude Zero in 1 fb^{-1}

Electroweak Physics



W and *Z* Production Leads to Rich Physics

- Essential tests of the Standard Model
- Higher order physics with Z p_T
- SM structure with dibosons (couplings, radiation amplitude zero)
- Constraints on Higgs mass through W mass
- Important backgrounds to many New Phenomena and other analyses

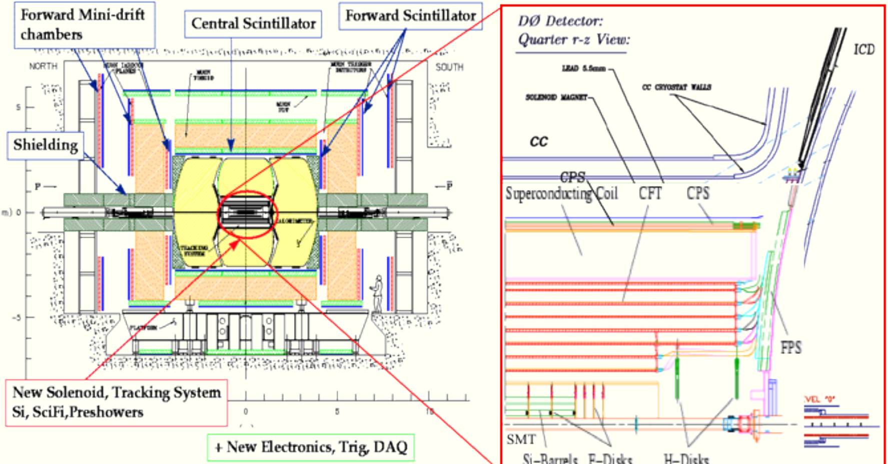
The DØ Experiment

- 84 institutions from 19 countries
- $\sim$ 600 Physicists

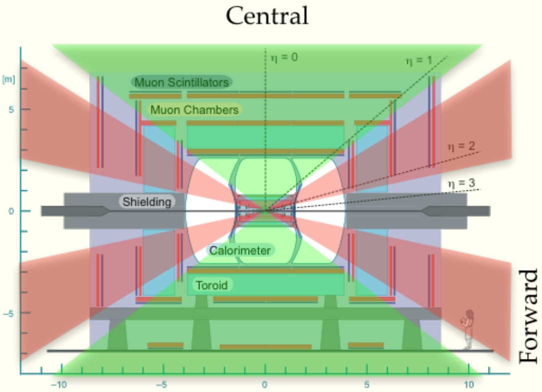
DØ Detector

- General purpose high p_T detector
- Excellent coverage for electrons ($|\eta| < 3.2$)
- Excellent coverage for muons ($|\eta| < 2.0$)
- Hermetic calorimetry for missing E_T measurement

DØ Detector in a Diagram

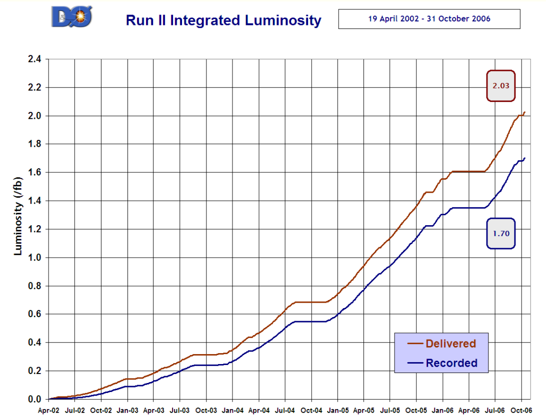


Calorimeter Regions for Electrons



- Central electrons (Central calorimeter - CC): $|\eta| < 1.1$
- Forward electrons (End Cap calorimeter - EC):
  Typically $1.5 < |\eta| < 2.5$

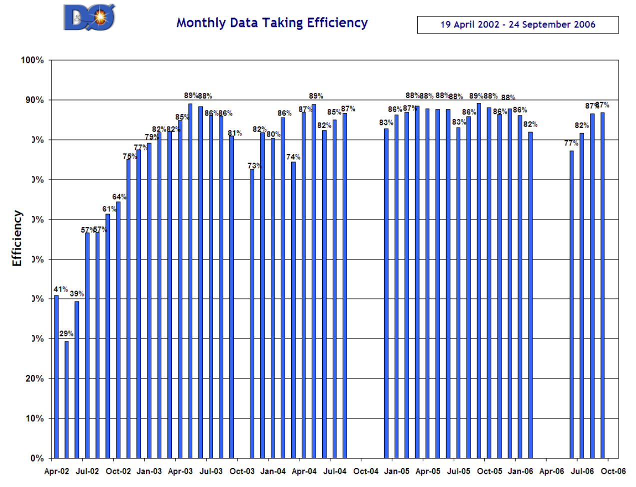
Luminosity



Results are due to excellent performance of the Tevatron

Results shown here are from our 1 fb^{-1} sample

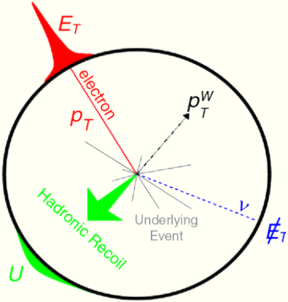
Efficiency



We work hard to make every delivered pb^{-1} count

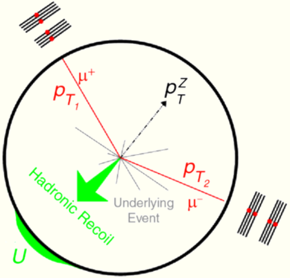
Leptonic decays are clean low background signatures

W Bosons



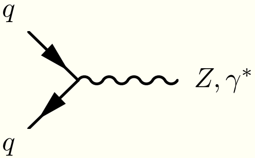
- High p_T e or μ
- Missing E_T from ν

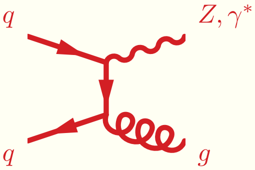
Z Bosons

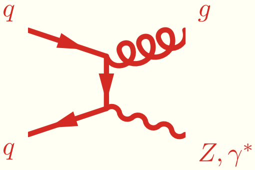


- Two oppositely charged e or μ with high p_T

$d\sigma / dp_T$ for $Z/\gamma^* \rightarrow e^+e^-$



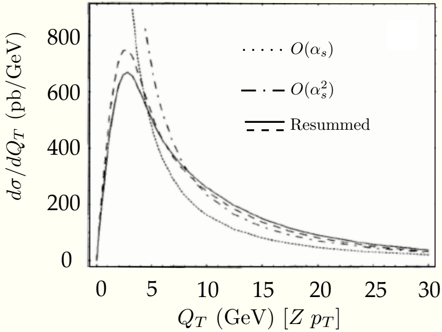


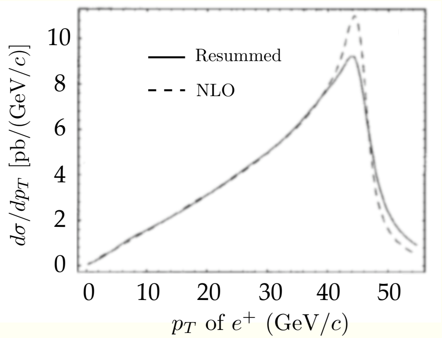


Z Transverse Momentum

- Z boson production governed by strong force
- $q\bar{q}$ annihilation gives no p_T to Z
- BUT, if a gluon is radiated by incoming (anti-)quark, then p_T is generated

Resummation

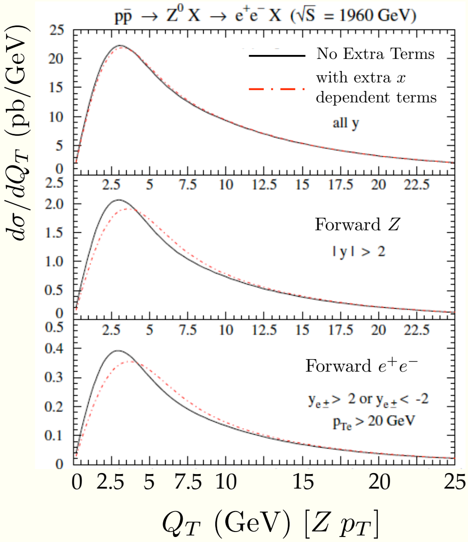




Balázs & Yuan (PRD 52:5558, 1997)

- Perturbative QCD governs high Z p_T
- For small Z p_T, cross section diverges due to soft gluon radiation!
- Solve with resummation - CSS (Colins, Soper, & Sterman) formalism
- Formalism has three free parameters. One of them, g_2, is important for Z p_T and is an input in some simulations

Broadening for forward Zs



- There may be additional x dependent effects not accounted for by the standard resummation
- Add an extra x term to the resummed form factor
- Effect is to broaden the Z p_T distribution for $x < 10^{-2}$
- *W* and Higgs too
- If effect exists, could be substantial at the LHC

Berge, Nadolsky, Olness, & Yuan (PRD 72:033015, 2005)

Analysis Goals

- Test the vector boson production formalism
- Help to reduce the theory uncertainty (g_2 is essential for precise W mass measurement)

Notes:

- Analysis with Z bosons is more precise than with W bosons
- Have ~ 1 fb^{-1} of data and $\sim$ 5,000 forward Z bosons $(|y| > 2)$

Deliverables

- Precision measurement of the Z p_T spectrum, $d\sigma/dp_T$
- Experimentally determine g_2
- Verify (or not) broadening of spectrum for forward Z bosons

Select $Z, \gamma^* \rightarrow e^+e^-$

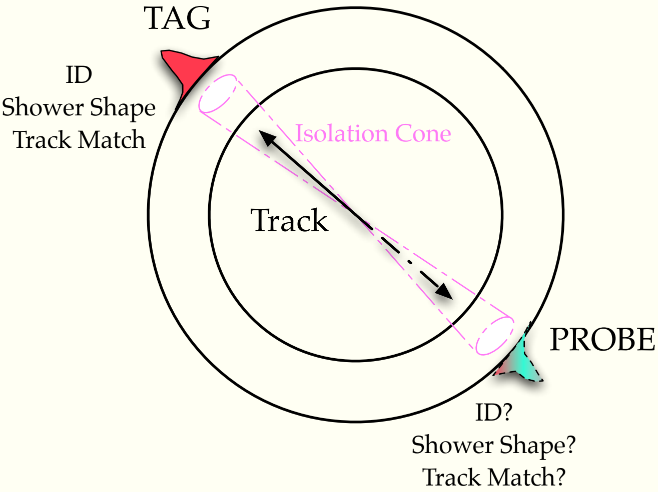
- Identify 2 electrons with $p_T > 25$ GeV/c
- Single electron trigger fired
- Electrons may be central (CC) $|\eta| < 1.1$
- ... or forward (EC) $1.5 < |\eta| < 3.2$
- If both central (CC-CC), then both must have a track match
- If one central and one forward (CC-EC) or both forward (EC-EC) then one must have a track match
- Invariant mass $70 < M_{ee} < 110$ GeV/c^2

Yields in 965 ± 58 pb^{-1}

CC-CC	CC-EC	EC-EC	Total
23,959	30,344	9,598	63,901

Efficiencies with Tag and Probe

Use $Z \rightarrow ee$ to study efficiencies with data



Efficiencies and Acceptance

Preselection efficiencies:

- Use tag and probe method; parametrized by electron p_T and pseudorapidity with much looser Z sample

Requirement	ϵ^{CC} (%)	ϵ^{EC} (%)
Electron ID	99.6 ± 0.1	99.2 ± 0.1
Spatial Track Match	90.5 ± 0.1	61.5 ± 0.3
Shower Shape	97.1 ± 0.1	96.9 ± 0.1

- Trigger efficiencies range from 96.6% to 99.0%

Signal ($Z/\gamma^* \to e^+e^-$) Monte Carlo

RESBOS(g_2 is input 0.68 is default) + PHOTOS + DØ Parametrized MC

Backgrounds

Multijet Di-jet events or EM+jet events (from W+jet or direct γ)

- Jets misidentified as electrons
- Use “bad” (fails shower shape requirement) EM sample to determine shape of “*ee*” invariant mass
- Fit candidate sample to linear combination of this shape and signal MC

Region	Background Fraction
CC-CC	1.30%
CC-EC	8.69%
EC-EC	3.79%
All	4.98%

Backgrounds continued

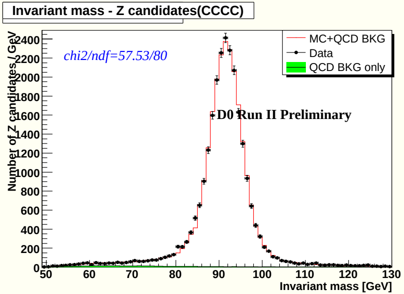
Z to taus $Z \to \tau\tau \to ee + 4\nu$

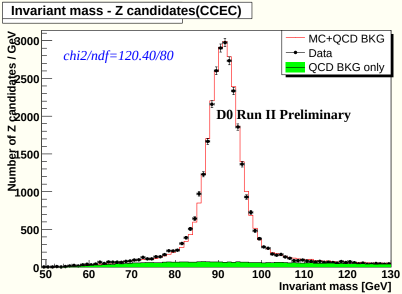
- Estimate contribution with MC.
- Expect 16.9 events in 1 fb^{-1}
- Negligible

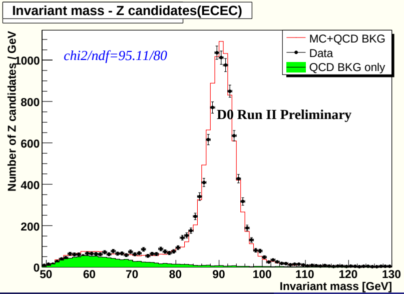
Dibosons WW, WZ, $W\gamma$

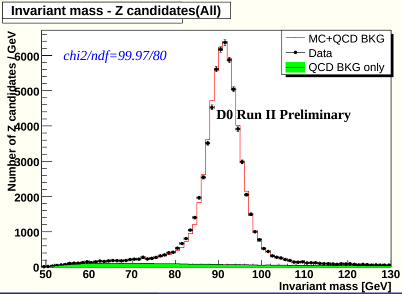
- Generates real electrons or electron+photon (latter is misidentified as an electron)
- Estimate contribution with MC
- Negligible

Invariant Mass   965 pb^{-1}

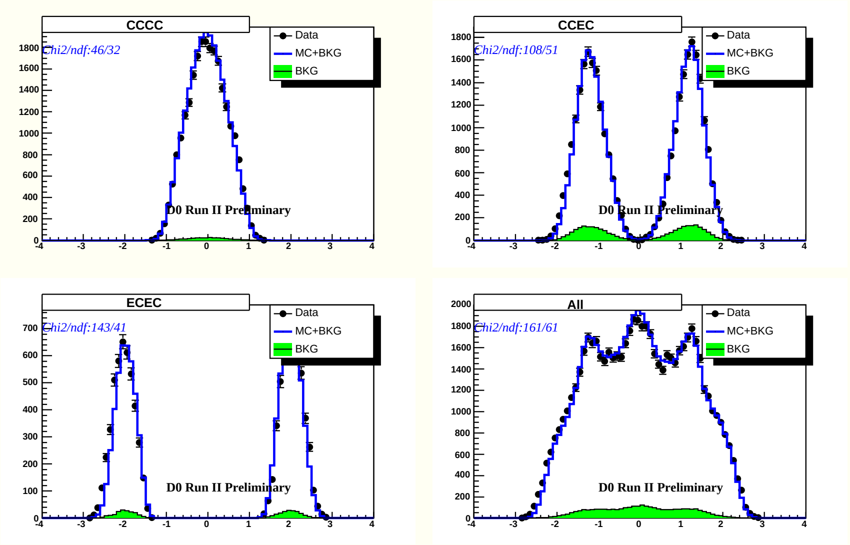








Pseudorapidity $965\ \text{pb}^{-1}$



Unfolding

To compare with theory, must remove smearing due to detector resolution effects

- Use the `RUN` program (Regularized Unfolding) by Blobel

Inputs

- Measured Z p_T in the data
- Z p_T of all generated signal MC events
- Z p_T of all smeared signal MC events (1-to-1 correspondence with above)
- Spurious Z p_T from the multijet background

- Passes tests for stability and closure

Systematic Uncertainties

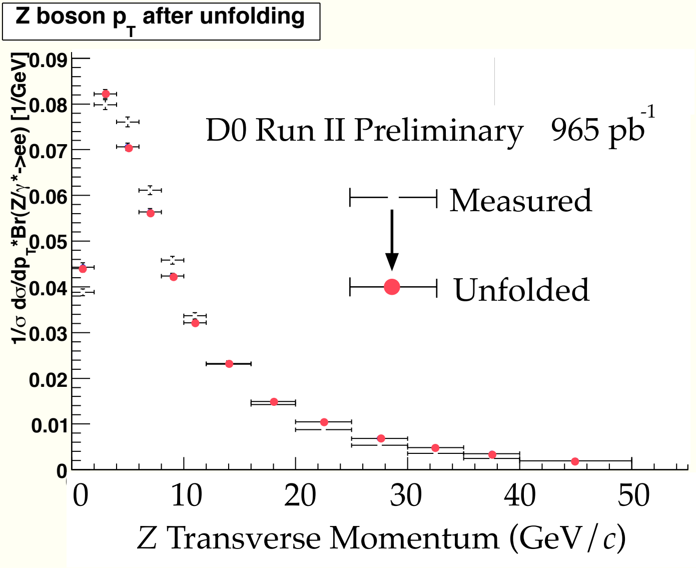
Smearing Energy scale, offset, and resolution
Shift smearing parameters within 1σ and note change to $Z\ p_T$. $< 4\%$. Most bins $< 2\%$

PDFs Use `RESBOS` with CTEQ6.1m PDFs. Shift within $\pm 1\sigma$ errors; gives 40 PDFs. Average uncertainly $\sim 3\%$

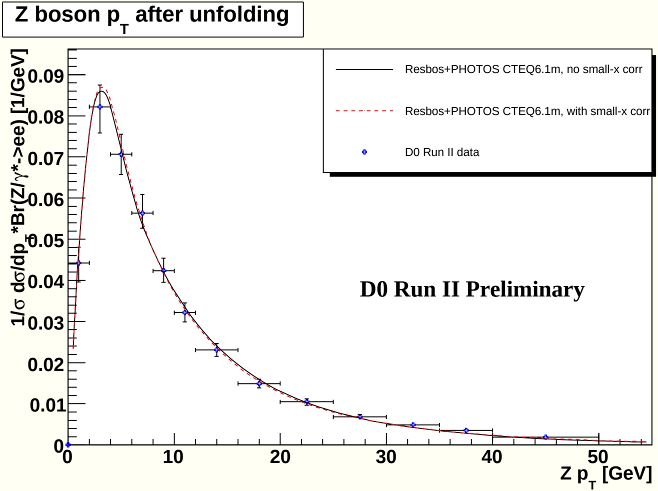
`RUN` Use smeared MC as data; do we get back generated MC? 3% for $p_T < 30$ GeV/c and 6% for $30 < p_T < 50$ GeV/c

ϵ $Z\ p_T$ dependence on Lepton ID efficiencies. Dominated by difference between data and full `GEANT` MC. 8% uncertainty. Under continued study. Largest Uncertainty

Unfolded Z p_T distribution



Compared to RESBOS with default $g_2 = 0.68$



Z p_T Wrap Up

Accomplished

- Measured the Z p_T spectrum for 965 ± 58 pb^{-1} (Preliminary)
- Compare to RESBOS

In progress:

- Working to reduce systematics
- Will extract g_2 (Very important for precise W mass)
- Will examine Z p_T for forward Z bosons to look for broadening at low x (Very important since if broadening exists for Z, it also exists for Higgs)

Improved Photon ID

Photon ID is challenging: absence of track, high multijet background, no observed high p_T photon resonance (like $Z \to ee$).

Improved Photon Identification

- Extensive studies of efficiencies and backgrounds with $Z \to ee$ data and full `GEANT` Monte Carlo
- Extends photon ID to forward region
- Investigates integration of central and forward preshower detectors for verification and pointing
- Automated tools for efficiency and background determination
- Methodology:
  - Treat photons as electrons; use $Z \to ee$ to tune selections
  - Measure photon efficiency with photon + jet MC (for $Z\gamma$)
  - Correct for e/γ shower difference with MC
  - Large data sample makes possible and accurate

Diboson Physics Introduction

$$W\gamma,\ Z\gamma,\ WW,\ WZ,\ ZZ$$

Important

- Opportunity to test cross sections and phonomena predicted by the SM
- Direct view of gauge boson “self couplings”
- New physics would be unambiguous
- Better understanding of backgrounds to New Phenomena and Higgs analyses

Diboson Physics Introduction

Exciting

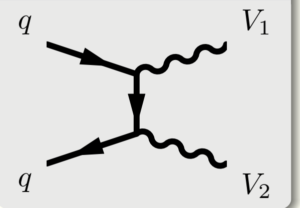
- In past two years, five W&C talks devoted to Dibosons

CDF	Waters	11/19/04	All
DØ	Diehl	1/28/05	All
DØ	Askew	6/23/06	$Z\gamma$, *WW*, *WZ* first evidence $(> 3\sigma)$
CDF	Lipeles	10/30/06	*WZ* first observation $(> 5\sigma)$
DØ	–This talk–		$Z\gamma$ & $W\gamma$ with 1 fb^{-1}

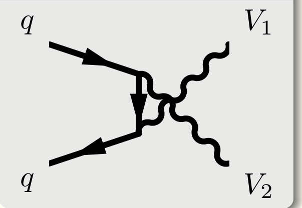
Boson Self-interactions

Non-Abelian $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ gauge symmetry leads to self-interactions for bosons in the SM

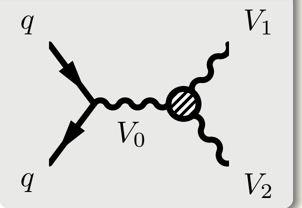
t-channel



u-channel



s-channel

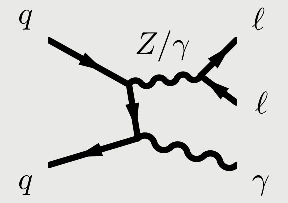


- Each diagram alone violates unitarity. But taken together the unitarity violation cancels out. Look for effects of this delicate balance
- NOTE: SM forbids $Z - \gamma$ self-interactions at tree level

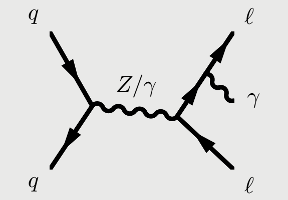
$Z\gamma$ Production

Only via:

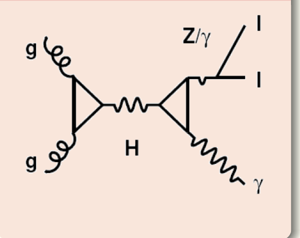
Initial State Radiation



Final State Radiation



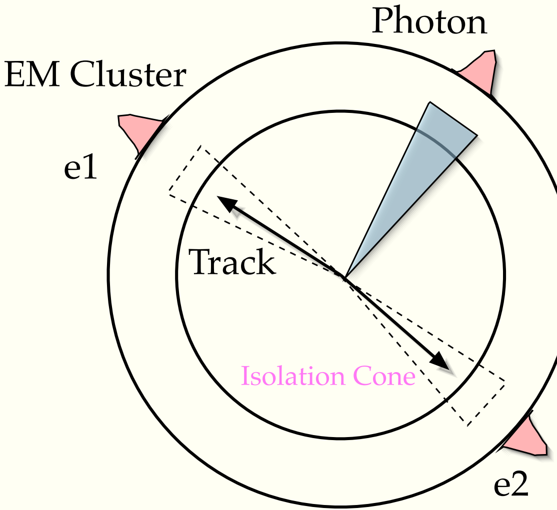
Something Exotic?



- Identify via leptonic Z decays + γ
- At $\sqrt{s} = 1.96$ TeV, SM (NLO) predicts*
  $\sigma(p\bar{p} \to Z\gamma \to \ell\ell\gamma) = 4.2 \pm 0.2$ pb

*$\Delta R_{e\gamma} > 0.7$, $E_T^{\gamma} > 7$ GeV, $M_{ee} > 30$ GeV/c^2

$Z\gamma$ Cartoon



$Z\gamma$ Anomalous Couplings

- Anomalous $ZZ\gamma$ and $Z\gamma\gamma$ couplings would increase σ resulting in higher E_T photons than SM

- To characterize non-SM couplings, use formalism:
  - Assume only Lorentz and gauge invariance
  - Use eight coupling parameters $h^V_{1\ldots4}$ where V is Z or γ
  - Two are CP violating ($i = 1, 2$) and two are CP conserving ($i = 3, 4$)

  - Ensure unitarity with form factor†

$$h_i^V = \frac{h_{i0}^V}{(1 + \hat{s}/\Lambda^2)^{n_i}}$$

  - In SM, all couplings here are zero

† $\sqrt{\hat{s}}$ is parton center-of-mass energy, Λ is form factor scale, and n_i is form factor power = 3 or 4

$Z\gamma$ Analysis Goals

- Test standard model $ZZ\gamma$ and $Z\gamma\gamma$ predictions
- Look for non-SM effects
- Look for exotic physics in $Z\gamma$ mass spectrum
- Use 1 fb^{-1} data

Deliverables

- Measure $\sigma(p\bar{p} \to Z\gamma \to \ell\ell\gamma)$
- Compare with standard model and discover AC or set limits
- Measure $M_{\ell\ell\gamma}$ spectrum and look for resonances

Previous DØ analyses

300 pb^{-1} results previously published:

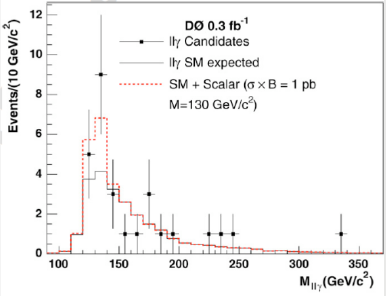
σ + AC limits

- PRL 95, 051802 (2005)
- Examined 290 $\ell\ell\gamma$ events
- $\sigma(\ell\ell\gamma) =$
  $4.2 \pm 0.4 \pm 0.3$ pb
- Compare to NLO SM
  $3.9^{+0.1}_{-0.2}$ pb
  ($E_T^\gamma > 8$ GeV here)
- AC Limits for $\Lambda = 1$ TeV

$$h_{30}^Z < 0.23 \quad h_{40}^Z < 0.020$$
$$h_{30}^\gamma < 0.23 \quad h_{40}^\gamma < 0.019$$

Bump hunt for scalars

- PLB 641, 415 (2006)
- No statistically significant excess for $X \rightarrow Z\gamma$



1 fb^{-1} $Z\gamma$ analysis

Use *ee* channel in 1026 ± 61.6 pb^{-1} of data

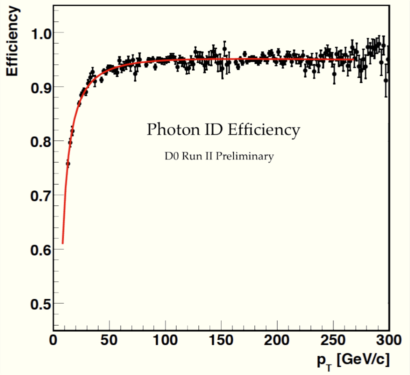
Select Z bosons

- Require two identified electrons
- One must be in CC $|\eta| < 1.1$, other may be in CC or EC ($1.5 < |\eta| < 2.5$)
- One must have $p_T > 25$ GeV/c, other > 15 GeV/c
- Both must match to a track
- Single electron trigger fired
- $M_{ee} > 30$ GeV/c^2

	CC-CC	**CC-EC**
Yield (events)	40,513	27,521
Efficiency	$(72.3 \pm 2.1)\%$	$(54.7 \pm 3.0)\%$

$Z\gamma$ Photon ID $\quad$ 1026 pb^{-1}

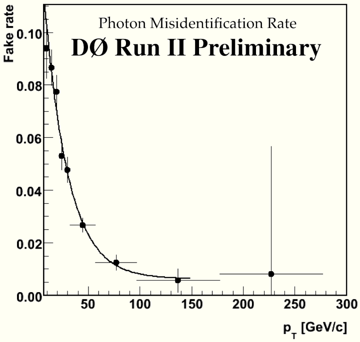
- Isolated EM shower in CC ($|\eta| < 1.1$)
- No nearby track on photon candidate path
- $> 96\%$ of energy in EM calorimeter layers
- $p_T > 7$ GeV/c
- Not near either electron, $\Delta R_{e\gamma} > 0.7$, $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$
- $> 90\%$ efficient for high p_T photons, 53% at 7 GeV/c



	CC-CC	CC-EC	Total
$Z\gamma$ Yield	256	131	387

$Z\gamma$ Backgrounds

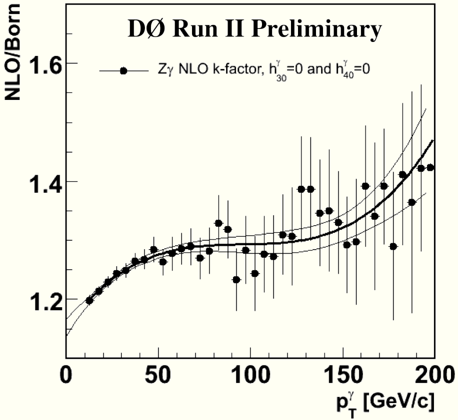
- Z + jets where a jet is misidentified as an electron is the only non-negligible background
- Measure mis-identification rate using multijet sample (jet triggered)
- mis-id rate is rate that EM-like objects pass photon selection
- Remove contamination by real photons (with photon purity from MC)
- Normalize by number of very loose photon candidates in Z boson sample to number in multijet sample.



	CC-CC	CC-EC	Total
Bkg	$18.3 \pm 3.0 \pm 2.9$	$14.8 \pm 2.5 \pm 2.2$	33.1 ± 6.4

$Z\gamma$ Signal Simulation

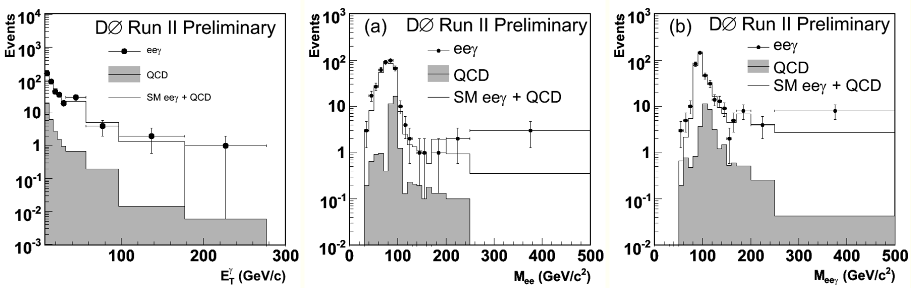
- Use Baur Leading Order $Z\gamma$ generator (has ISR, FSR and Drell-Yan)
- But NLO is important; use Baur NLO generator with just ISR to determine *k* correction factor
- Then use parametrized MC to determine acceptance and reconstruction efficiencies



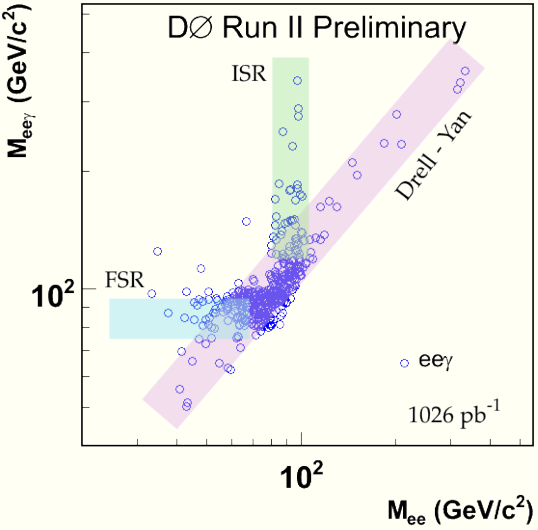
	CC-CC	CC-EC
$\epsilon \times A$	0.053 ± 0.003	$0.023 \pm 0.002_{\text{stat+sys}}$

$Z\gamma$ Results   1026 pb^{-1}

- SM Predicts 327.3 ± 19.5 events $Z\gamma \rightarrow ee\gamma$
- 33.1 ± 6.4 events background from Z+jet
- SM + Bkg = 360.4 ± 20.6 events
- We observe 387 $Z\gamma \rightarrow ee\gamma$ events



$Z\gamma$ Processes Seen



Combined CC-CC/CC-EC cross section for $1026 \pm 61.6\ \mathrm{pb}^{-1}$

$$\sigma \times BR(Z\gamma \to ee\gamma) = 4.51 \pm 0.37_{\mathrm{stat+sys}} \pm 0.27_{\mathrm{lum}}\ \mathrm{pb}^*$$

NLO Prediction is $\sigma \times BR(Z\gamma \to ee\gamma) = 4.2 \pm 0.2$ pb

For $E_T^\gamma > 7$ GeV, $\Delta R_{e\gamma} > 0.7$, $M_{ee} > 30\ \mathrm{GeV}/c^2$

To do:

- Add muon channel
- Set limits on $ZZ\gamma$ and $Z\gamma\gamma$ anomalous couplings
- Bump hunt with 1 fb^{-1}

* This approved preliminary result uses the old luminosity constant. Result being prepared for publication uses the new luminosity constant.

$W\gamma$ Introduction

- Direct look at $WW\gamma$ coupling
  - For $W\gamma$ production, only $WW\gamma$ couplings are visible
  - For WZ, only WWZ couplings
  - For WW both are visible and their relation is an assumption (LEP)
- Test Standard Model
- Unambiguous signs for new physics (higher cross section, higher E_T spectra)
- Perhaps measure anomalous electric and magnetic moments of W boson
- Standard Model Predicts a Radiation Amplitude Zero not yet observed (described in detail in a few slides ahead)

$WW\gamma$ Anomalous Couplings

Use effective Lagrangian formalism:

$$L_{WW\gamma} = -ie\left[(W^{\dagger}_{\mu\nu}W^{\mu}A^{\nu} - W^{\dagger}_{\mu}A_{\nu}W^{\mu\nu}) + \kappa_{\gamma}W^{\dagger}_{\mu}W_{\nu}F^{\mu\nu} + \frac{\lambda_{\gamma}}{M_W^2}W^{\dagger}_{\lambda\mu}W^{\mu}_{\nu}F^{\nu\lambda}\right]$$

- First term: minimal coupling of γ and W; fixed by W charge
- Second term: κ and λ relate to electromagnetic moments

In the SM: $\kappa_{\gamma} = 1$ and $\lambda_{\gamma} = 0$

Physical quantities

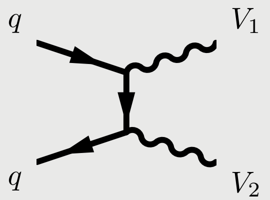
These couplings are related to physical W boson properties

Moment	**Full form**	**SM Value**
Magnetic Dipole	$\mu_W = e(1 + \kappa_{\gamma} + \lambda_{\gamma})/2M_W$	e/M_W
Electric Quadrupole	$Q^e_W = -e(\kappa_{\gamma} - \lambda_{\gamma})/M_W^2$	$-e/M_W^2$

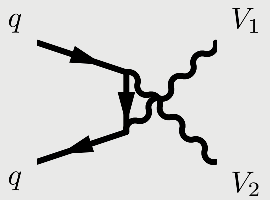
Boson Self-interactions

Non-Abelian $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ gauge symmetry leads to self-interactions for bosons in the SM

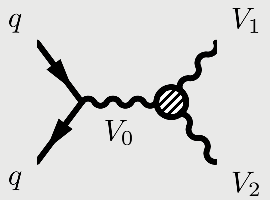
t-channel



u-channel



s-channel

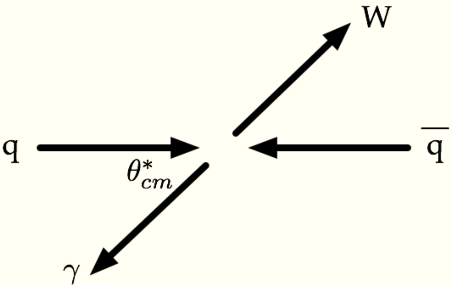


- Each diagram alone violates unitarity. But taken together the unitarity violation cancels out. Look for effects of this delicate balance
- NOTE: SM forbids $Z - \gamma$ self-interactions at tree level

$W\gamma$ Radiation Amplitude Zero

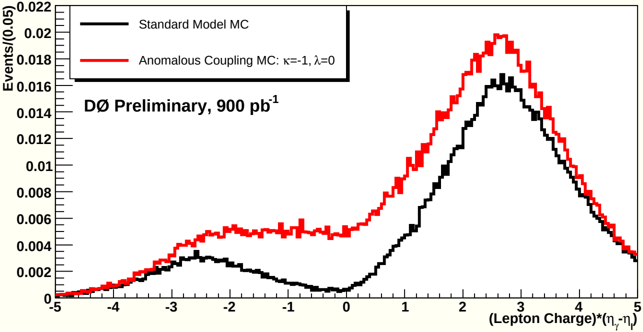
The balance of the three diagrams in the SM leads to destructive interference

- Manifests as a zero in the angle distribution between the photon and the incoming quark in the center of mass frame
- $\cos(\theta^*) = \pm 1/3$ where $+$ is for W^-



- But the unknown ν direction makes $\cos(\theta^*)$ ambiguous
- Fortunately, the W and γ directions are correlated, and so the lepton from the W and the γ directions are correlated
- Measure instead the charge-signed rapidity difference
- In the SM, $\mathrm{sign}(\ell)[y(\gamma) - y(\ell)] \approx -0.3$

Radiation Amplitude Zero Continued



- with $E_\gamma > 7$ GeV, $\Delta R_{\ell,\gamma} > 0.7$, Three body mass > 110 GeV/c^2 to reduce FSR
- Integral of curves normalized to their expected cross sections with respect to the SM, which is set to unity

More Radiation Amplitude Zero Continued

Never before observed

Potential spoilers of RAZ

- Final state radiation has no radiation amplitude zero; fills in dip
  (Our requirements minimize FSR)
- Other SM backgrounds do not have RAZ; fill in dip
  (Keep background small)
- NLO effects reduces the correlation between the lepton and the photon; fills in dip
  (Not a big problem here; but makes $W\gamma$ more difficult at LHC)
- Anomalous couplings reduce or eliminate balance; fills in or eliminates dip
  (New Physics! Woohoo!)

$W\gamma$ Analysis Goals

- Use the e and μ decays of the W in the 1 fb^{-1} data
- (Hadronic channel is swamped by multijet background)
- Use forward photons for best acceptance

Deliverables

- Investigate Radiation Amplitude Zero
- Measure $W\gamma$ Cross Section
- Discover or set limits on anomalous couplings

$W\gamma$ Event Selection

$W \rightarrow e\nu$

- Select identified isolated electron with $p_T > 25$ GeV/c
- Electron may be in CC $(|\eta| < 1.1)$ or EC $(1.5 < |\eta| < 2.5)$
- Electron must be matched to a track
- Missing $E_T > 25$ GeV
- Event must pass a single electron trigger

$W \rightarrow \mu\nu$

- Select identified muon isolated in calorimeter and tracker with $p_T > 20$ GeV/c
- Missing $E_T > 20$ GeV
- No additional muons or tracks with $p_T > 15$ GeV/c
- Event must pass a single muon trigger

More Requirements

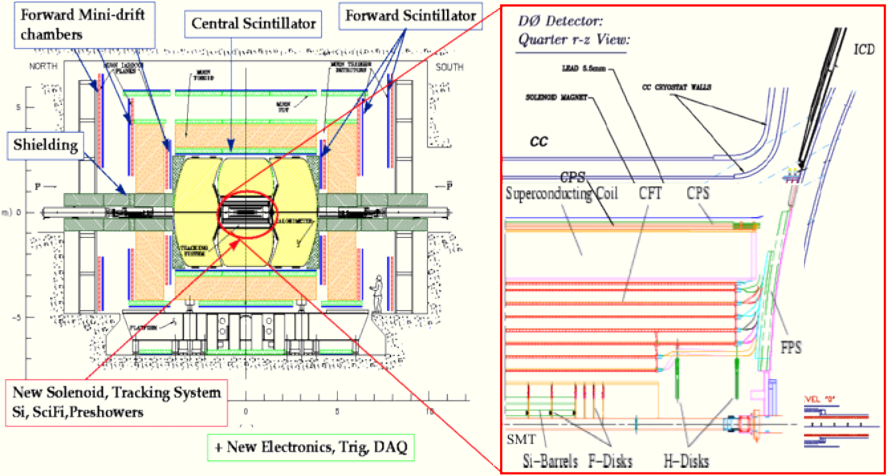
Photon ID

- Photon may be central (CC) or forward (EC)
- $E_T^{\gamma} > 7$ GeV
- Photon is isolated in calorimeter and tracker
- Shower shape is consistent with EM object
- Photon has an associated cluster in a preshower detector
- Photon and lepton must be separated $\Delta R > 0.7$

Other

- To reduce FSR, $M_{T^3} > 110$ GeV/c^2
- To further reduce FSR, $M_T(e\nu) > 50$ GeV/c^2
- To reduce $Z \rightarrow ee$, $89 < M_{e\gamma} < 99$ GeV/c^2
  - Optimized for minimal fractional uncertainty on signal
  - Asymmetric - $W\gamma$ has more events below M_Z than above

DØ Detector in a Diagram



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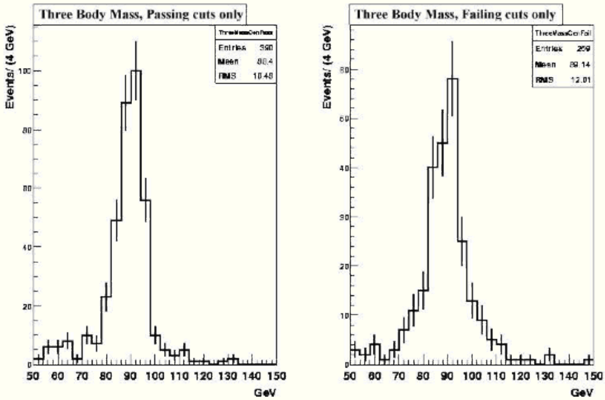
Efficiencies and Acceptances

- Efficiency of ID requirements for e, μ determined by $Z \to ee$ data with tag and probe method
- Acceptance ($W\gamma$ passing kinematic and geometric requirements) determined by ...
  - Baur LO MC with k factor for NLO and Pythia to determine initial boost.
  - Parametrized MC used for smearing
- Difficult to calculate γ efficiencies from data
  - Use full GEANT MC with data minbias overlay
  - Isolation and EM fraction for low energy γ affected by ambient calorimeter energy. Ambient energy in $Z \to ee$ data agrees well with GEANT
  - but...

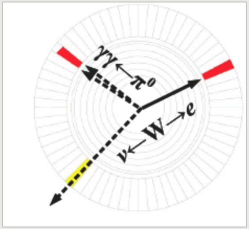
Using $Z\gamma$ for Photon ID efficiency

- No easy handle for low energy γ reconstruction efficiency, but...
- Use $Z\gamma$ FSR events for photons with $E_T < 25$ GeV
- For $E_T > 25$ GeV, use GEANT and scale with $Z \to ee$ data/MC comparison



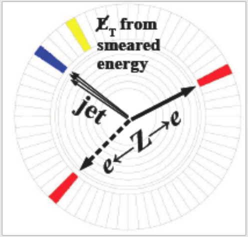
Backgrounds

W + jet



- Jet misid as γ
- Dominant background in both channels
- Estimated with data
- S/B $\sim$ 1

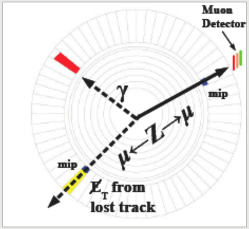
ℓeX



- e misid as γ
- Significant in e channel ($Z \rightarrow ee$)
- Estimated with data

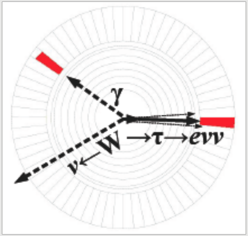
Backgrounds Continued

$Z\gamma$



- Missing or mismeasured lepton
- Significant in muon channel
- Estimated with MC

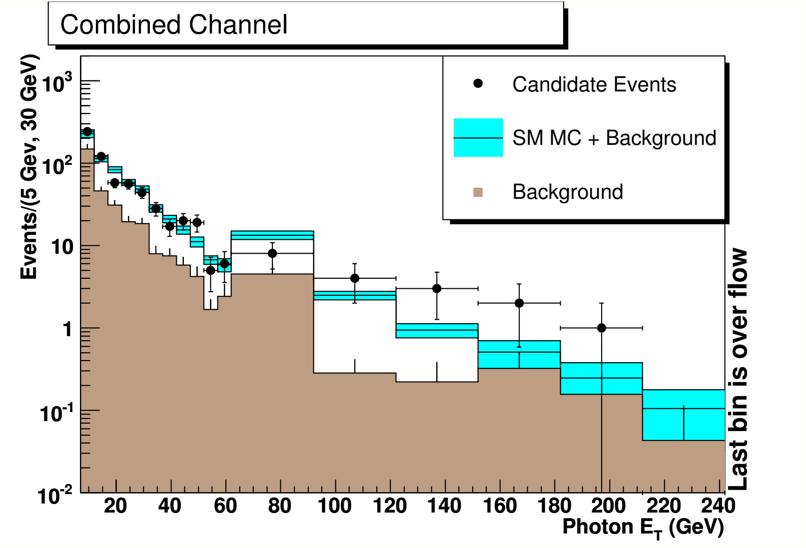
$W\gamma \to \tau\nu\gamma$



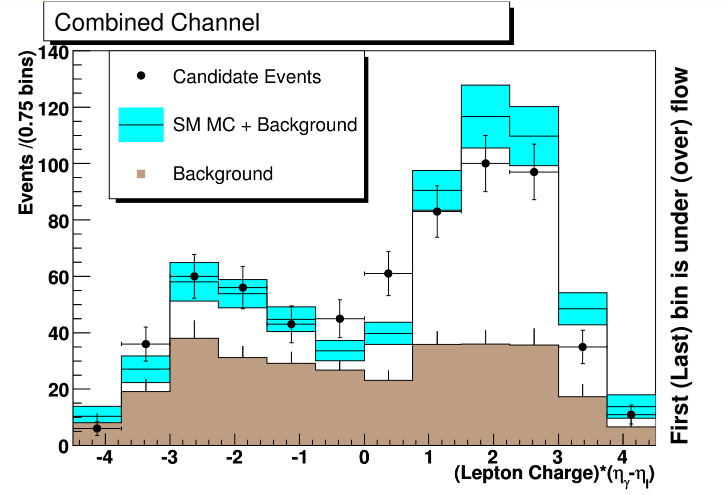
- Estimated with MC

	μ channel	e channel
Luminosity	878 pb^{-1}	933 pb^{-1}
$\epsilon \times A$	0.046 ± 0.003	0.071 ± 0.007
Candidate Events	245	389
W + jet Bkg	98 ± 12	$148 \pm 17_{\text{stat+sys}}$
ℓeX Bkg	6 ± 2	$34 \pm 4_{\text{stat+sys}}$
τ Bkg	2.6 ± 0.4	$1.7 \pm 0.2_{\text{stat+sys}}$
$Z\gamma$	8 ± 1	
Expected Signal	130 ± 9	211 ± 14
Measured Signal	130 ± 18	205 ± 26
Measured $\sigma \times BR$ (pb)	$3.21 \pm 0.49 \pm 0.20$	$3.12 \pm 0.49_{\text{stat+sys}} \pm 0.19_{\text{lum}}$

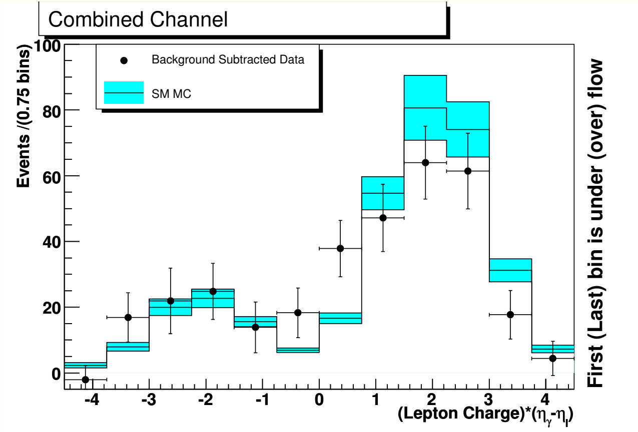
Note: SM $\sigma \times BR = 3.21 \pm 0.08_{\text{PDF}}$ pb
with respect to $E_T^{\gamma} > 7$ GeV, $\Delta R_{\ell\gamma} > 0.7$, and $M_{T3} > 90$ GeV


Combined Channel
Candidate Events
SM MC + Background
Background
Events/(5 Gev, 30 GeV)
10^3
10^2
10
1
10^{-1}
10^{-2}
20 40 60 80 100 120 140 160 180 200 220 240
Photon E_T (GeV)
Last bin is over flow

Rapidity Difference 900 pb^{-1} PRELIMINARY



Rapidity Difference 900 pb^{-1} PRELIMINARY



- Distribution is consistent with SM ($\chi^2 = 16/12$ DOF)
- Shape is indicative of destructive interference from RAZ
- Do we see the Radiation Amplitude Zero? Quantify...

Quantifying the dip

Shape Test

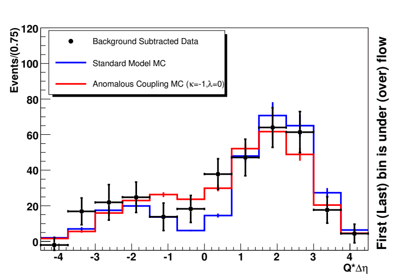
- Compare data shape to an alternative hypothesis
- χ^2 test of the normalized distributions
- Alternative hypothesis is AC $WW\gamma$ coupling $\kappa = -1$, $\lambda = 0$
- Turns off W magnetic dipole moment
- Rapidity difference is dipless (unimodal)

Dip Test

- Measure statistical significance of observed dip
- Compare number of candidates in dip to number in peak
- Addresses if dip is a statistical fluctuation

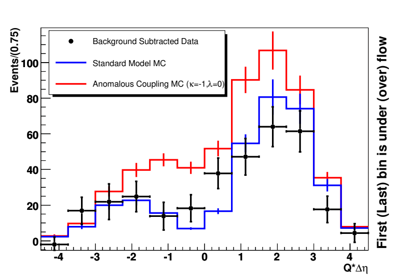
Shape Test 900 pb^{-1} PRELIMINARY

Float Normalization



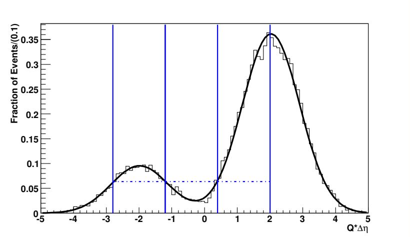
- Normalization is allowed to float (not really fair)
- Unimodal hypothesis is consistent with data at $\chi^2 = 9/11$ DOF

Fixed Normalization



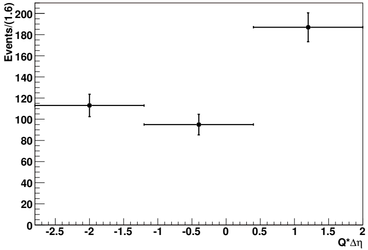
- Normalization fixed by cross sections
- AC enhances $\sigma(W\gamma)$
- This hypothesis fits at $\chi^2 = 55/12$ DOF

- Determine probability that dip is a statistical fluctuation
- Use three bins
  - 1: sample small peak
  - 2: sample dip
  - 3: sample big peak



- Measure $R_1 = N_{dip} / N_{small}$, $R_2 = N_{dip} / N_{big}$
- Then by definition, if R_1 and $R_2 < 1$ there is a depletion of events in the expected region
- Use SM MC to find bin breaks (expected positions of dip and peaks)

- Probability of no dip = Prob($R_1 \geq 1$ or $R_2 \geq 1$)
- From the data (DØ PRELIMINARY)
  $R_1 = 0.841 \pm 0.117$
  $R_2 = 0.508 \pm 0.064$
- Assuming Gaussian errors, the dipless hypothesis is ruled out at 90% C.L.



Also used a standard statistical method‡ that is binless. Consistent with these results.

‡J.A. Hartigan and P.M Hartigan, “The Dip Test of Unimodality”, Annals of Statistics **13**, 70-84 (1985)

Accomplished

- Observed $W\gamma$ final state. Production rate consistent with SM
- Measured the $W\gamma$ charge signed rapidity difference
  - Consistent with SM
  - Shape is indicative of the Radiation Amplitude Zero with unimodal hypothesis ruled out at 90% C.L.
  - Will be able to make stronger statements with more luminosity

- To do: Use charge signed rapidity difference and photon E_T spectrum to set limits on $WW\gamma$ AC couplings

SUMMARY

- Electroweak Physics is extremely interesting and important
- With 1 fb^{-1}
  - Measured Z p_T (resummation, g_2)
  - Measured $\sigma(p\bar{p} \rightarrow Z\gamma \rightarrow ee\gamma)$. Agrees with SM
  - Measured charge signed rapidity difference in $W\gamma$. Agrees with SM. First investigation of Radiation Amplitude Zero
- More data to look at
- More results ahead